LASER ULTRASOUND FOR THE STUDY OF THIN SHEETS

C. Edwards, A. Al-Kassim* and S.B. Palmer

Department of Physics
University of Warwick, UK

INTRODUCTION

Laser ultrasound is now an accepted and mature technology. However it is still seeking its first fully commercial industrial application although there are several potential uses in prototype form. The major advantage of laser ultrasound is that it is a non contact technique and can therefore be used on hot or moving components. The pulsed laser source generates simultaneously longitudinal and shear bulk waves and Rayleigh surface waves. When the material is in the form of a thin sheet the latter propagate as Lamb or plate waves providing the ultrasonic wavelength is greater than the sheet thickness.

Applications employing all the acoustic modes described above are under investigation and many are described in the companion papers in this volume. The present paper describes the use of laser ultrasound for the generation and detection of Lamb waves to study thin sheets and in particular to measure the sheet thickness.

LAMB WAVES

The generation and detection of Lamb Waves using non-contact techniques has been discussed in several recent papers (1,2). We will restrict ourselves here to the minimum necessary to pursue the applications to be described later. The Lamb wave mode propagates in a plate when the plate thickness is much greater than the ultrasonic wavelength. There are a range of Lamb wave modes with the fundamental symmetric(s_0) and antisymmetric(a_0) modes being relevant to the present study. The frequency dependence of the

* Par Industrial ApS
Odense, Denmark

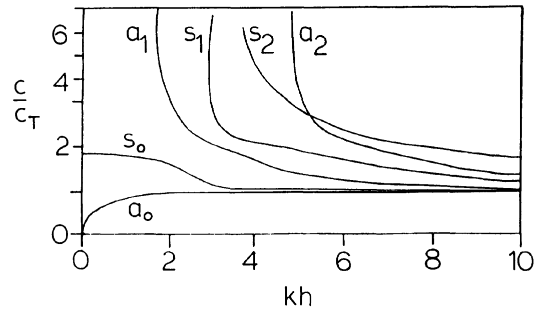

Figure 1. Typical Lamb wave dispersion curves. $C/_{CT}$ is the velocity normalised to the shear wave and kh is the frequency thickness product.

mode velocities are shown in Fig. 1, from which it is clear that at relatively low frequencies (or thin plates) the velocity of s_0 approximates to the longitudinal velocity and is frequency independent while a_0 is strongly dispersive with the velocity falling to zero as the wavelength tends to infinity.

For thick plates and/or high ultrasonic frequencies both modes converge to the Rayleigh (surface) wave velocity. The transfer from Rayleigh to Lamb waves as the plate decreases in thickness has been demonstrated elsewhere (3), using a Q-switched Nd:YAG laser as ultrasonic generator and in plane and out of plane sensitive EMATs as detectors (fig. 2).

It is immediately obvious from Fig. 2 that the symmetric and antisymmetric waves are clearly separated in thin plates. The symmetric wave has a pulse like feature while the antisymmetric wave is strongly dispersive with the high frequency components arriving before the low frequencies. The degree of dispersion increases as the plate thickness decreases. Careful examination of the symmetric arrival also shows evidence of dispersion but in this case it is the low frequencies that arrive first and the high frequencies later.

It has been shown elsewhere (1) that if the limiting velocity of the symmetric wave C_{sheet} is known then the dispersion of the antisymmetric wave can be used to determine the thickness t of the plate supporting the wave. From the relationship for the group velocity, Cg

$$C_g^2 = (4\pi ft/\sqrt{3})\ C_{sheet} \tag{1}$$

where

$$C_{sheet} = [4\left(\frac{\lambda+\mu}{\lambda+2\mu}\right)\frac{\mu}{\rho}]^{1/2}$$

λ and μ are the Lamé constants

ρ is the density

and f is the frequency

it is clear that a plot of velocity squared against frequency should yield a straight line with slope dependent on the plate thickness.

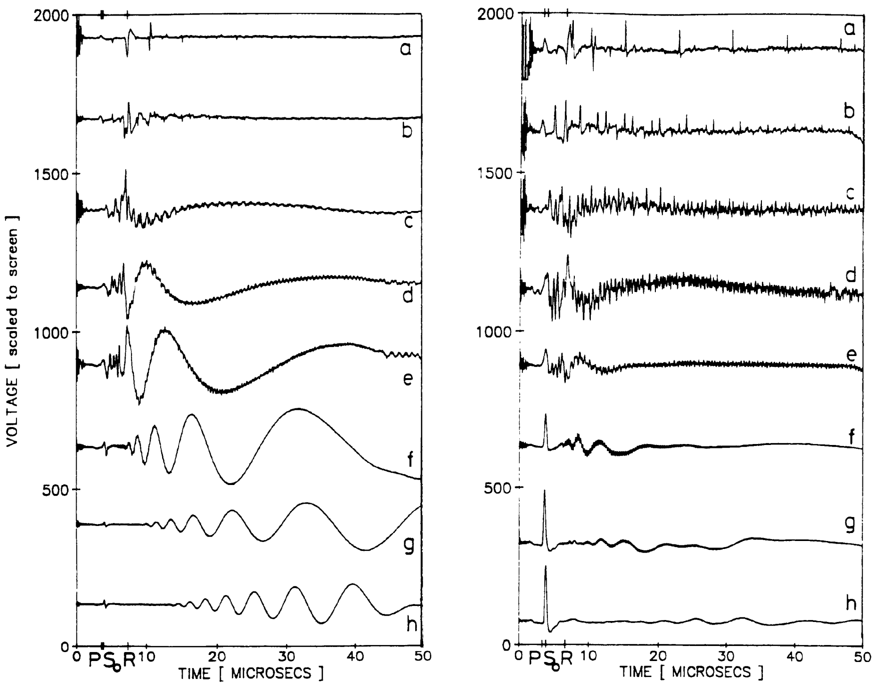

Figure 2. EMAT detected Lamb waves in aluminium plates. a) 12.80 b) 6.36 c) 3.26 d) 1.72 e) 1.14 f) 0.44 g) 0.21 and h) 0.11 mm thick.

EXPERIMENTAL DETAILS

A fast rising short time period laser pulse (10 and 50 ns respectively) will generate a broadbandwidth ultrasonic pulse with frequency components ranging from well below 1MHz up to ~ 20MHz. It is therefore the ideal source of Lamb waves. For efficient generation the laser wavelength has to be chosen such that there is high absorption in the target material. Thus Nd:YAG lasers are suitable for metals ($\lambda = 1.06\ \mu m$) while CO_2 ($\lambda = 10.6\ \mu m$) is ideal for plastics.

At least three generation mechanisms are available, thermoelastic where the surface of the sample is heated without changing its phase (4), the plasma regime where a small amount of material is ablated away (5) and the shock wave regime which is particularly relevant to CO_2 laser pulses incident on a metal surface (6). The thermoelastic regime is not very efficient but if true nondestructive testing is required it may be the only one that can be employed.

There are more options available for non contact Lamb wave detection. EMATs can be employed as in Fig. 2 but will only work on conducting surfaces and at stand-off distances of up to ~ 2mm. Laser interferometers have many advantages, they are truly remote, they have a very wide bandwidth and can give absolute displacements. However relatively simple, modified Michelson, interferometers (7) require highly polished surfaces and are very sensitive to the position and orientation of the surface. Fabry-Perot interferometers will operate satisfactorily on rough surfaces (8) but require considerable financial investment that may not always be justified by the application.

Beam deflection systems with knife edge techniques are particularly suited to Lamb wave detection (9) since they can be used in either reflection or transmission mode. They lack sensitivity and bandwidth when compared to interferometers but this is not important in the present example since the Lamb waves have large amplitudes and we are particularly interested in the low frequency components. Beam deflection systems are however sensitive to vibrations/displacements of the plates or sheets.

Air coupled transducers are now being evaluated in this context since again they can operate at low frequencies with relatively high sensitivity. However they may be immune to mechanical vibrations, they are cheap, will work off any surface and can operate at a stand-off of up to a few centimetres.

TESTING OF MATERIALS

Typical Lamb waves generated by pulsed laser and detected by a laser interferometer are shown for aluminium in Fig. 3 and for silicon in Fig. 4. The silicon waveform in particular shows clear evidence of the dispersion present in both s_0 and a_0. This compares favourably with the theoretical waveform developed by Spicer et al (10) (Fig. 4 insert).

The particular application we shall concentrate on here is the measurement of the thickness of plastic film while it is being extruded. There is a need during the extrusion process to monitor the thickness of the sheet across the whole of its width at regular intervals along the length. The film ranges in thickness, depending on application, from 10 -150 μm and thickness is required to $\pm$ 0.1 μm if possible. As always the manufacturers specify the impossible.

Our aim was to develop a system that would be installed on a bubble

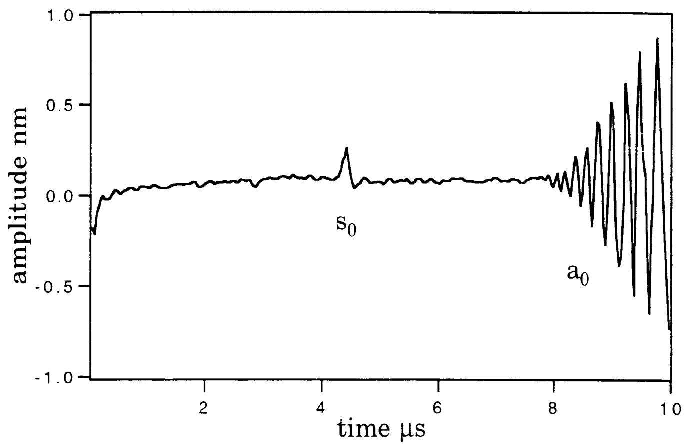

Figure 3. Laser generated Lamb wave on 30 μm aluminum plate.

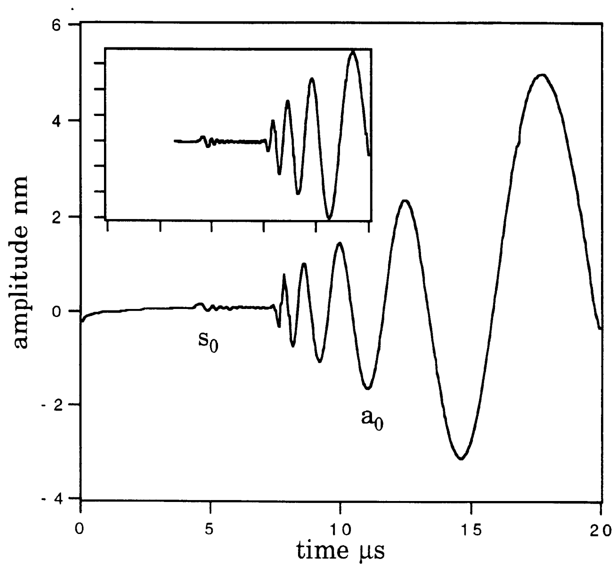

Figure 4. Laser generated Lamb wave on 50 μm Silicon wafer. (Insert - theory after Spicer et al).

extrusion system at Otto Nielsen in Copenhagen, Denmark. The bubble system extrudes the plastic film in the form of a cylinder and the cylinder moves vertically upwards at a rate of ms^{-1}. After trying a range of alternatives the optimum system is shown in Fig. 5. The ultrasound is generated by absorption of a pulsed $C0_2$ laser with rise time of 50 nsec and pulse width of 100 nsec. The laser pulse is focused by a cylindrical lens to a line parallel to the axis of the bubble. This provides optimum efficiency for generation of Lamb waves around the circumference of the bubble.

The Lamb wave is detected by a 2 mw He-Ne laser reflected from the bubble surface some 3 cm from the source. A split photodiode feeding a differential pre-amplifier was used as the detector, when the He-Ne beam falls equally on both halves the output is zero, the low frequency components were used to drive a mechanical acctuator to maintain the optimum sensitivity. The bandwidth of the system was 1 kHz to 10 MHz. Movements of the bubble surface tend to misalign the system and the feedback system is necessary for reliable measurements, however the $\pm$ 3mm movement on the detector was barely adequate.

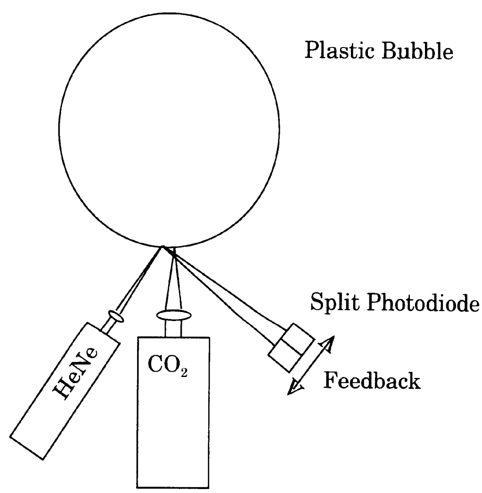

Figure 5. On line measurement of plastic sheet thickness.

A typical waveform is shown in Fig. 6 where the dispersion of the a_0 mode can be clearly seen. This was taken in sheet nominally 100 μm thick while it was moving at 4 ms^{-1} and hot (100°C). Fig. 7 shows the experimental velocity squared frequency plot compared to equation 1. No visible damage is caused to the plastic sheet. Table I shows the result of a real time analysis of 10 successive laser shots (repetition rate 4Hz). The random scatter is of the order of $\pm$ 1 μm in thickness determination. However if these ten results are averaged and compared to the following ten (Table I) then it is clear that the target of $\pm$ 0.1 μm is within reach.

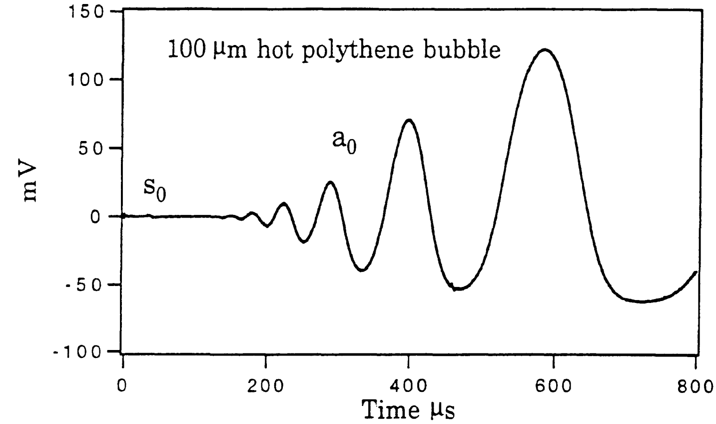

Figure 6. Typical waveform obtained on hot plastic film.

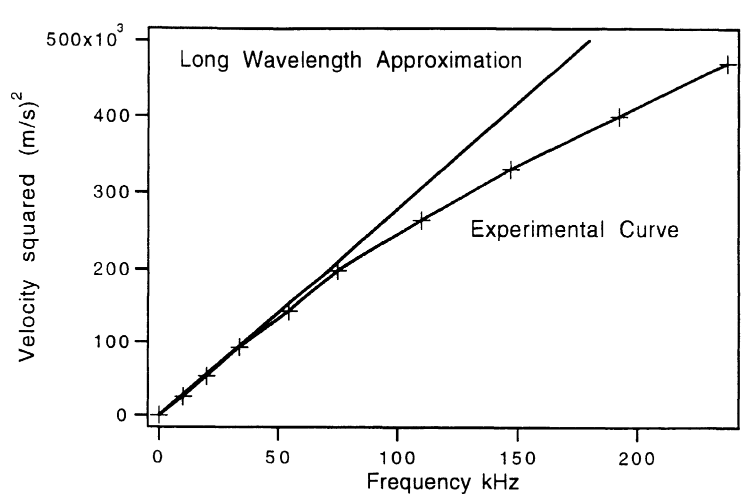

Figure 7. Velocity squared/frequency graph derived from Lamb wave data.

FUTURE DEVELOPMENTS

The CO_2 laser is a convenient reliable and relatively cheap source of Lamb waves in plastic sheets. However the shot to shot variations are caused by inadequacies in the optical detector system. A possible alternative is the air coupled detector and we have evaluated this as a possibility. However it also has severe problems. Firstly its spatial resolution is poor, secondly there is a time delay introduced by the ultrasound wave having to propagate through the air from sheet to transducer, thirdly it is sensitive to any air borne shock wave travelling directly from the source.

Table 1. On Line Thickness Measurement Of Plastic Sheet

SHOT NO.	ULTRASONIC THICKNESS (μm)	ULTRASONIC THICKNESS (μm)
0	90.1	92.2
1	91.8	92.4
2	93.4	93.0
3	92.3	91.7
4	92.0	92.8
5	92.4	92.1
6	92.4	92.2
7	93.0	93.0
8	93.1	92.3
9	92.9	91.4
10	91.9	90.5
Mean	92.3 μm	92.2 μm

We attempted to eliminate some of these effects by screening the source from the detector and by using a focused transducer operating at 120 kHz. The waveforms obtained using the arrangement in Fig. 8 are shown in Fig. 9. The 'knife edge' and air coupled signals are similar for the early part of the a_o waveform but the air coupled trace soon deteriorates due to interference through the air.

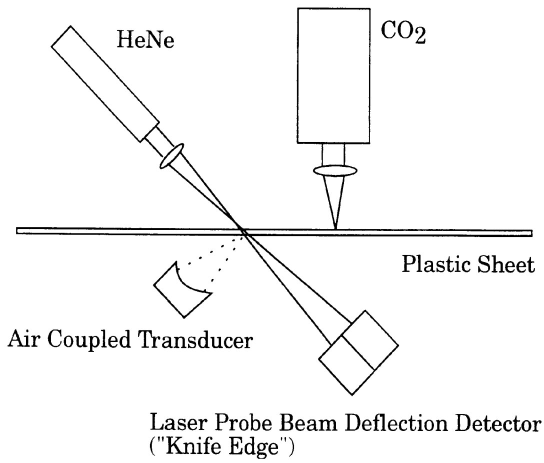

Figure 8. Experimental arrangement for comparing Air-Coupled Transducer and "Knife-Edge" detector.

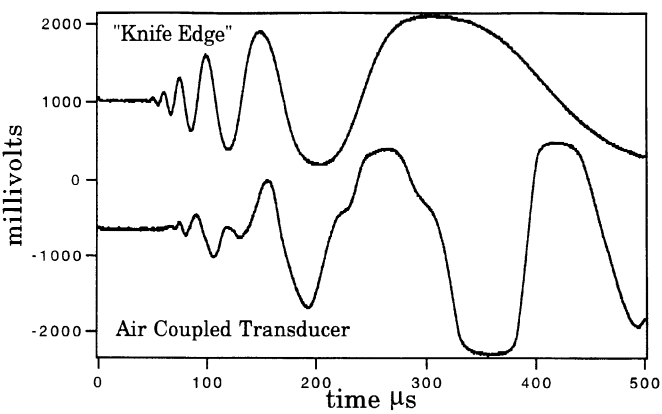

Figure 9. Comparison of laser probe ("Knife-Edge") and Air Coupled Transducers as detectors.

CONCLUSIONS

We have demonstrated that a laser ultrasound system can be used to detect Lamb waves in thin plastic sheets as they are being manufactured. The waveforms can be used to provide an accurate estimate of the sheet thickness in real time. There is great potential for a commercial system although improvements in the detection are required. Initial attempts to use an air coupled transducer as detector have proved promising.

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